Pleistocene eolianites and low sea levels

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1. Introduction

Eolianites are lithified eolian deposits most commonly preserved in the form of eolian limestones; they formed on the coastal and lowland areas of islands around the world between 55ºN and 45ºS, where relatively constant winds and warm weather occur. They are usually related to subtropical marine platforms or tropical (Tucker & Wright, 1990) or temperate (James & Clarke, 1997) areas with abundant carbonate production. Notable outcrops occur in the Mediterranean, South Africa, southern Australia, and Caribbean areas (Brooke, 2001).

Eolianites form at low latitudes in both hemispheres and are a distinctive feature of the Pleistocene sedimentary record (Abegg, *et al*., 2001; Brooke, 2001; Fornós et al., 2002a; Nielsen *et al*., 2004; Radies *et al*., 2004; Sivan & Porat, 2004; Munyikwa, 2005; Andreucci *et al*., 2006; Andreucci *et al*., 2010a). The record preserved in eolian deposits can be accurately dated (Price *et al*., 2001; Frenchen et al., 2004) and can be used to evaluate the complex relationships with other deposits including marine terraces, alluvial and colluvial deposits and/or paleosols to obtain important paleoclimatic information, including sea level oscillations and landscape evolution (Kindler *et al*., 1997; Carew & Mylroie, 2001; Kindler & Mazzolini, 2001; Rose *et al*., 1999; Preusser *et al*., 2002; Coltori *et al*., 2010; Elmejdoub *et al*., 2011).

In the western Mediterranean the Pliocene-Pleistocene successions including eolianites are widespread in many coastal areas (Andreucci *et al*., 2010b; Gutiérrez-Elorza *et al*., 2002; Nielsen *et al*., 2004; Fornós *et al*., 2009; El-Asmar, 1994). Middle to Late Pleistocene coastal carbonate successions where marine beach deposits alternate with eolianites and paleosols and/or colluvial deposits are also widely distributed in the Mediterranean area (Hearty, 1987; El-Asmar, 1994). The quick lithification of these carbonate eolianites upon subaerial exposure preserves a high-resolution stratigraphic record. In this sense, eolianite successions that outcrop extensively all around the

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island of Sardinia, which have been recently dated by modern techniques (Andreucci *et al.*, 2006, 2009, 2010b; Thiel *et al.*, 2010), are especially important.

The island of Mallorca (Balearic archipelago) located in the middle of the western Mediterranean (Figure 1) represents a classic area for the study of the Pleistocene deposits (including eolianites as well as marine terraces) and their relationship with climate and sea level change history (Butzer & Cuerda, 1962; Butzer, 1975; Cuerda, 1975; Hillaire-Marcel *et al.*, 1996, Hearty, 1987; Clemmensen *et al.*, 1997; Rose *et al.*, 1999; Clemmensen *et al.*, 2001; Fornós *et al.*, 2009). The Middle and Late Pleistocene Camp de Tir deposits contain the most extensive marine record (Bardají *et al.*, 2009) and host the type locality for Tyrrhenian marine deposits (i.e. *Strombus bubonius*-bearing) in the Balearics (Hearty *et al.*, 1986; Cuerda, 1989; Goy *et al.*, 1997; Zazo *et al.*, 2003). Most of these deposits rest on Miocene limestones (Pomar *et al.*, 1985) and, although they appear all around the coasts of Mallorca, they are particularly well-exposed in the southern part of the island.

This paper is a review and deal with the Pleistocene sedimentary record of Mallorca in the context of the geological setting of the island. We will describe the characteristics of the sedimentary facies, mainly the eolianites, their petrology, vertebrate tracks, trackways, and rhizocretions. We will focus on the description of the Late Pleistocene eolian sequences, their architecture and characteristics. Finally, the paleoclimatic and sea-level oscillation implications during the Middle and the late Pleistocene are discussed.

2. Geological and environmental setting

Mallorca, the largest island of the Balearic archipelago, is located in the temperate climate area of the middle of western Mediterranean Sea. This archipelago corresponds to the eastern emergent part of the so-called Balearic Promontory, a mostly submarine

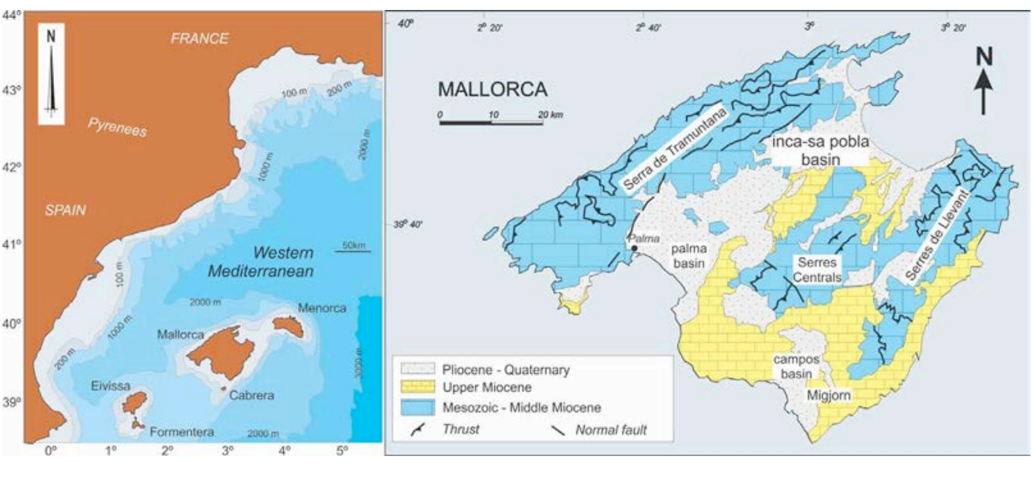

Figure 1. Location of Mallorca in the Western Mediterranean and geological sketch map showing main structural and stratigraphical elements.

relief extending from the Iberian Peninsula to Menorca, the north-eastern most island of the archipelago. It represents the thickened continental crustal unit forming the NE continuation of the Alpine Betic thrust and fold belt build during the Middle Miocene (Gelabert *et al*., 1992), that resulted from the continental collision between the African and the lberian plates. The normal faulting that affected Mallorca during the Middle Miocene-Pleistocene times gave way to a set of horsts (ranges) and grabens (plains) that characterized the present-day physiographic appearance of the island.

The stratigraphic record ranges from the Carboniferous to the Quaternary, with the common feature being carbonate deposits. Mainly Mesozoic to Paleogene deformed deposits crop out in the resultant structured relief of the ranges (Serra de Tramuntana and Serres de Llevant), while post-orogenic sediments cover the Neogene basins (Fornós & Gelabert, 1995). These depressed areas are filled with a thick sequence of Plio-Pleistocene deposits (Figure 1).

These Plio-Pleistocene deposits range from continental sediments (conglomerates, sands and red silts) related to erosional processes of the highest mountain ranges of the island, to calcareous and fossiliferous sands that correspond to beach and dune deposits of coastal environments that reflect the Pleistocene sea-level oscillations.

The most important Quaternary deposits in Mallorca are located in the northern bays of Alcúdia and Pollença on the north-eastern coast, the Palma bay in the south-western coast, and Campos bay in the south. Modern deposits are characterized by a beach-dune-lagoon system extending a variable distance along the coastline, flanked by folded Jurassic and Cretaceous limestones (Figure 2). Pleistocene marine, colluvial, fluvial and eolian deposits of variable thickness cover most of these outcrops. Holocene and recent coastal dunes in the lowlands have been stabilized by shrub vegetation. The presence of notches and littoral platforms, understood as marks corresponding to the high-stand sea levels, are conspicuous features in the southern and eastern parts of Mallorca, shaping rock coasts developed on Upper Miocene calcarenite deposits.

The climate of the island is typical of the Mediterranean, with very hot, dry summers and mild, wet winters. The mean temperature is roughly 17ºC, with mean winter and summer values of 10 and 25ºC, respectively. The mean annual precipitation is about 500 mm and is mostly concentrated in autumn (Guijarro, 1986).

The wind regime in the northern bays is characterized by westerly and northerly winds (annual frequencies of winds over 4 m/s are 27% and 17% respectively) (Servera, 1997). The island's location is very favorable to the development of sea breezes (Ramis *et al*., 1990); these are very often present from April to November, and occur almost every day during the summer. Wind velocities associated with sea breezes are generally approximately 3 m/s, but velocities as high as 10 m/s are not uncommon (Ramis, 1998).

Two clear Mediterranean community types form the characteristic vegetation: holm oaks, *Cyclamini-Quercetum ilicis*, with boreal characteristics abundant at the mid-altitudes and macchia and garrigue bushes *Oleo-Ceratonion, Hypericion balearici, Rosmarino-Ericion* mainly in the dry lowlands (Bolòs, 1996).

3. The Pleistocene sedimentary record of Mallorca

The work of Butzer and Cuerda (1962) started the comprehensive scientific study of Pleistocene deposits in Mallorca. Pleistocene sedimentary deposits, outcropping patchily along the majority of Mallorca's coastline, provide an unsurpassed record of glacial and interglacial climate, atmospheric circulation patterns and eustatic sea levels. Since then, this Pleistocene record has been thoroughly described and discussed in the literature, establishing Mallorca as one of the classic localities in the study of the marine Pleistocene in the western Mediterranean basin (Bardají *et al*., 2009).

The existing literature began with the works of Butzer (1962) and Butzer and Cuerda (1962) in the second half of the twentieth century and reached its maximum expression in the comprehensive books of Cuerda (1975, 1987, 1989). These books provide a complete and excellent record of the paleo-sea levels based on fossil beaches, and additionally incorporate extensive paleoclimatic information based on the paleontological content (Cuerda, 1987, Gómez-Pujol *et al*., 2007).

Although composed mainly of eolian and littoral marine facies, the Mallorcan deposits also comprise a wide spectra of colluvial, fluvial, and alluvial fan facies. The interfingering of the various facies give the deposits a complex sedimentary architecture (Rose *et al*., 1999; Fornós *et al*., 2009; Clemmensen *et al*., 2001).

As the Balearic Islands represent a relatively stable area with negligible or very minor tectonic activity (Hearty, 1987; Fornós *et al*., 2002a; Giménez, 2003; Silva *et al*., 2005), results from Pleistocene studies are relatively easy to interpret because there are no tectonic effects to be adjusted for from the effects of the sea-level change. This fact gives to these studies a special relevance and more meaningful results. For this reason, Mallorca is one of the areas of major interest for much recent research concerning the register and evidences of sea-level changes forced by large Pleistocene climatic oscillations.

Sea-level oscillations have been deduced by the analysis of marine terraces and accompanying geomorphologic imprints (Cuerda, 1989; Goy *et al*., 1997; Zazo et al., 2003), the analysis of eolian sequences (Clemmensen *et al*., 1997) and their correlated soils (Rose *et al*., 1999; González-Hernández, *et al*., 2001; Nielsen *et al.,* 2004; Muhs *et al*., 2010), as well as from the stratigraphy of eolian, colluvial and alluvial fan deposits (Clemmensen *et al*., 2001; Fornós *et al*., 2004, 2009).

The first accurate chronological data by means of modern technologies on Mallorcan deposits took place at the second half of the last century, which included U/Th (AAR) methods on marine shells (Stearns & Thurber, 1965; Hearty *et al*., 1986; Hearty, 1987; Hillaire-Marcel *et al*., 1996; Goy *et al*., 1997; Zazo *et al*., 2003), and paleomagnetic analyses (Nielsen *et al*., 2004). From the former references it is possible to identify at least four highstands: three during MIS 5e, at 135 kyr and 117 kyr (two events); and the fourth, at ca. 100 kyr (MIS 5c or 5a). Additionally, there are more recent and precise data based on U-series geochronology, on sea level history based on phreatic overgrowths in speleothems obtained in littoral caves in eastern and southern Mallorca (Ginés & Ginés, 1972; Vesica *et al*., 2000; Tuccimei *et al*., 2006; Onac *et al*., 2006; Tuccimei *et al*., 2012). Conflicts arise between the two-generation of proxies due to discrepancies between ages of events. In these caves, three highstands have been recognized (Tuccimei *et al*., 2006) corresponding to MIS 5e (138-128 and 122-116 kyr) and one more in MIS 5a (82-80 kyr) (Dorale *et al*., 2011; Tuccimei *et al*., 2012).

4. Petrology of eolianites (the sediment)

4.1 Some terminological aspects of eolianites

Eolianites are windblown deposits (dunes and less commonly eolian sand sheets) of carbonate composition (some authors also use eolianites for deposits poor in carbonate!) that are usually associated with coastal environments that have undergone rapid carbonate deposition. Initially described by Sayles (1931), the terminology has changed over time with variable differences in characterization (including emplacement and composition): from backshore lithified carbonate sands (Davis, 1983) to eolian limestone (or carbonate eolianite) with more than 50% of carbonate constituents (Abegg *et al*., 2001). The current use of the term 'eolianite' in a broad sense refers to a coastal calcarenite that corresponds to the accumulation of dune deposits that consist of reworked carbonate marine (mainly bioclastic) sands (Brooke, 2001) that have undergone carbonate cementation, and which have been deposited in a

Figure 2. The Late Pleistocene colluvial, fluvial and eolian deposits in the northern bay of Alcúdia flanked by folded Jurassic and Cretaceous limestones. Height cliff *ca*. 10 m.

coastal carbonate environment (Fairbridge & Johnson, 1978) during the Quaternary (Gardner, 1983).

4.2 Sedimentary characteristics of the Mallorcan eolianites

Bioclastic sand is the principal constituent of the Mallorcan eolianites (Figure 3). The main components include red algae (constituting more than 50%), followed by fragments of molluscs (mostly bivalves and gastropods), echinoids, benthic foraminifera, bryozoans and other marine unidentified bioclastic grains. Peloidal grains are present and a small proportion of calcareous lithoclasts (mainly dolomite) can also be observed at specific geological settings. Ooids are scarce and are only present in Early Pleistocene deposits (Calvet, 1979).

The bioclastic composition of the eolian sand reveals that the nearest shallow marine environments are the source of the sediment. This ancient platform had an ecosystem similar to the present Balearic carbonate platform (Fornós & Ahr, 1997, 2006), where biotic and textural characteristics vary with depth. Sea grasses (mainly *Posidonia oceanica* meadows) extend across the inner and the middle ramp, sheltering and protecting a variety of calcareous organisms. Most of the modern beach and dune sediments consists of bioclasts derived from the communities that thrive in the seagrass meadows, but the greatest volume of skeletal carbonates is produced as bryozoan, rhodalgal and molluscan gravels that occur as patchy blankets, primarily on the middle ramp (Canals & Ballesteros, 1997). The accumulation and fragmentation of this skeletal material produces bioclastic sands that, once deposited on the beach by waves and marine currents, are wind-transported inland mainly by the dominant winds and by the constant and regular sea-breezes normal to the coasts.

In general terms, the eolian dune sediments are composed of fine to medium-grained bioclastic sands that were lithified by fresh-water cementation (Calvet *et al.*, 1980). The deposits are well sorted and typically composed of 2-5 mm thick laminae of medium to coarse sand alternating with very thin laminae of fine sand. This lamination, which we interpret as a type of pin-stripe lamination formed by migrating wind ripples (cf., Fryberger & Schenk, 1988), is overprinted by a crude rhythmic

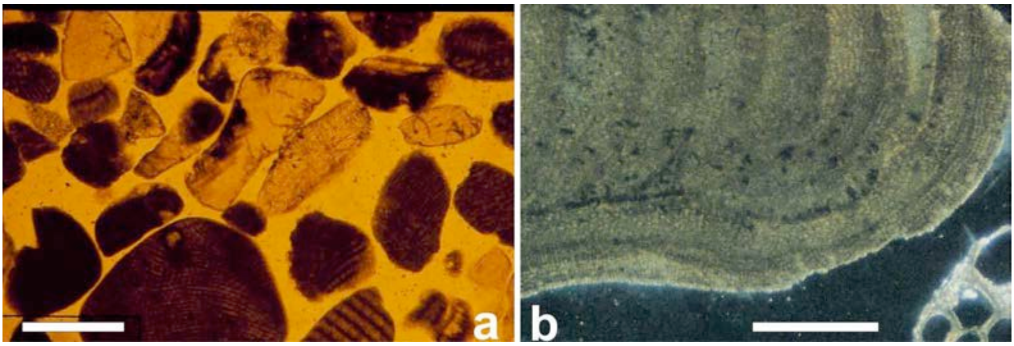

Figure 3. Thin sections showing that bioclastic sand is the principal constituent of the Mallorcan eolianites (a) Dune sediment viewed in plane polarized light, showing its bioclastic composition and the low degree of vadose cementation; (b) detail showing red algae as the main constituent. Scale bar 0.5 mm.

Inferred MIS	Marine cycle	Apparent sea level (in meters)	Faunal characteristics	Radiometric age
	Z3	2	Banal	Post-Roman
MIS 1	Z2	2	Banal	
	Z1	3	Banal	
MIS 2 to 4	Three eolianite generations		HEMICYCLE B	
MIS 5a	Y3	0.5 – 3	Probably banal	80,000 ± 5,000 BP
MIS 5e	Y2	1.5 – 2	Partial *Strombus* fauna	110,000 ± 5,000 BP
MIS 5e	Y1	9 – 15	Partial *Strombus* fauna	125,000 ± 5,000 BP
MIS 6	Two eolianite generations		HEMICYCLE C	
	X2	6.5 – 8.5	Impoversihed Senegalese fauna	190,000 ± 10,000 BP
MIS 7?	X1	2 – 4.5	Full *Strombus* fauna	210,000 ± 10,000 BP
MIS 8?	Two eolianite generations		HEMICYLCE D	
	W4	4 – 8	Banal	> 250,000 BP
MIS 9?	W3	15 – 18	*Patella ferruginea*	?
	W2	22 – 24	*Patella ferruginea*	
	W1	30 – 35	?	
MIS 10?	Three eolianite generations		HEMICYCLE E	
MIS 11?	V (22)	*ca.* 15	Banal	
	V (21)	45 – 50	Banal	
??	Two eolianite generations		HEMICYCLE F	
	U	30 (?)	*Patella ferruginea*	
??	?	60 – 65	?	
	?	75 – 80	?, *Purpura pleissi, Ostrea cucullata*	
	?	100 – 105		

Figure 4. The six continental hemicycles (F, E, D, C, B, A) from Butzer (1975). The eolianites, Early to Late Pleistocene in age, were arranged according to several criteria including the altitude (higher altitude means older age), the fauna content (differentiating cold and warm faunas) and some radiometric data.

Lamination (2-5 cm) and related to differential cementation of the laminae. The variation in the degree of cementation is tentatively ascribed to typical Mediterranean seasonal alternations of humid and dry periods (Fornós et al., 2002b). More rarely other eolianites contain laminae that can be interpreted as grain flow and grain fall deposits. The eolianites have cross-bedding of different types ranging from classical large-scale trough-formed and/or tabular cross-bedding to spectacular critical to supercritical dune cross-stratification formed by large climbing dunes (Clemmensen *et al.*, 1997, Clemmensen *et al.*, 2001)

4.3 Dating the eolianites

The first attempt to isotopically date Quaternary deposits from the Balearics was by Stearns & Thurber (1965) on marine molluscan shells from the Middle and Upper Pleistocene, which established the basis for correlation of later research, especially those from Cuerda (1975). This author made a detailed study of the Quaternary sediments by means of their faunal content, differentiating warm and cold faunas in the beach and dune sediments, thereby recognizing the main stages of the Pleistocene. Based on Cuerda's former work, Butzer (1975) arranged the eolianites into six continental hemicycles (F, E, D, C, B, A), Early to Late Pleistocene in age (Figure 4), according to several criteria including the altitude (higher altitude means older age), the fauna content (differentiating cold and warm faunas) and some radiometric data obtained by earlier techniques. Butzer (1975) separated the units into the last marine isotope stage (MIS 1; post-Roman), and three different eolianite generations (Hemicycle B, probably of MIS 4 to 2). After the identification of three marine highstands representing MIS 5 (80±5 kyr for MIS 5a; 110±5 kyr for MIS 5c?; 125±5 kyr for MIS 5e), he separated two other eolianite generations (Hemicycle C, probably MIS 6). MIS 7 is represented by two marine highstands (190±10 kyr and 210±10 kyr), which lie below two more eolian generations of the Hemicycle D (probably MIS 8). MIS 9 is defined by four possible highstands at different altitudes with an age older than 250 kyr, covered with three new eolianite generations (Hemicycle E, that must correspond to the MIS 10). The highstands of MIS 11 and older (perhaps MIS13) are separated by two more eolianite generations (Hemicycle F).

Aminostratigraphy has been used extensively in the Mediterranean (Hearty, 1986; Hearty *et al.*, 1986; Miller *et al.*, 1986), especially in Mallorca by Hearty *et al.*, (1986, 1987) and Rose *et al.* (1999) to date the individual lithostratigraphic units. The mollusc shells corresponding to marine deposits were used to make the allo/isoleucine as well as U/Th (by alpha technique) measurements. The lack of precision of both methods and the presence of reworked shells did not allow unequivocal assignment of each marine unit with a precise highstand. Hearty's work documented the chronology of Camp de Tir section, which was deposited during MIS 5.

Hillaire-Marcel *et al.* (1996) developed a pioneering work on the marine deposists of the Camp de Tir section, near Palma, using precise U-series dating by means of thermal ionization mass spectrometry (TIMS). This approach permitted precise location of the chronostratigraphic events reflected in the Tyrrhenian deposits resulting in the definition of two highstands during the Last Interglacial as well as dating of the faunal changes concurrent with it. As the Holocene to Upper Pleistocene eolian sequences are interbedded (Bardají *et al.*, 2009) with marine deposits in southern Mallorca (Camp de Tir in Palma and Campos bay), these eolian deposits have been correlated from different outcrops by means of the U/Th radiometric dating of the marine terraces bearing *Strombus bubonius* that characterize the MIS 5e highstand (González-Hernández *et al.*, 2001; Bardají *et al.*, 2009).

Nielsen *et al.* (2004) described the geochronologic framework of the Middle Pleistocene carbonate eolian sequences by means of magnetostratigraphy and susceptibility stratigraphic analysis supplemented by luminescence dating. The Els Bancals sequence in southern Mallorca consists of alternating colluvial and eolian deposits resting on an eroded marine platform, probably corresponding to the sea-level highstand of MIS 11 (427-364 kyr) as indicated by the presence of beach deposits. Nielsen *et al.*, (2004) recognize several eolian periods in the eolian-colluvial sequence deposited during the interval 333±70 kyr (eolianites at the base of the sequence) to 275±23 kyr (eolianites at the top of the sequence). The presence of three reversal excursions that can be correlated with the Levantine (400–360 kyr), the CR1 (325–315 kyr), and the CR0/BiwaIII excursions (280–260 kyr) suggests that the cyclic terrestrial succession at Els Bancals was deposited during insolation peaks 38–24 (Laskar et al, 1993), which correlates with MIS 11–8 (410 to 260 kyr).

Paleomagnetic surveys have also been used by González-Hernández *et al*. (2000) to date eolianite deposits appertaining to the Lower Pleistocene (Matuyama epoch) for the Badia Blava (eastern part of Palma bay) eolianites and the even older Upper Pliocene eolian deposits at Banc d'Eivissa, which crop out respectively in east and west sides of Palma Bay.

Recent contributions offer a detailed Upper Pleistocene sea-level curve obtained by means of U-series analysis (TIMS) on phreatic overgrowths in speleothems (Vesica *et al*., 2000; Fornós *et al*., 2002a; Tuccimei *et al*., 2006; Dorale *et al*., 2010). This sea-level curve shows at least three highstands during the Last Interglacial (80-82 kyr MIS 5a, 116-122 kyr and 128-138 kyr both from MIS 5e), matching the highstands identified by study of the marine terraces (Hillaire-Marcel *et al*., 1996; Goy *et al*., 1997; Zazo *et al*., 2003; Bardají *et al*., 2009). This scenario permits the assignation of at least two cemented eolian units, which occur interbedded with paleosols, to the pre-isotopic substage 5e and another two to the Last Interglacial (MIS 5). Additionally, three other eolian units have been identified in the Last Glacial (MIS 4 to 2), which present a variable cementation and are separated by erosional surfaces or weak soil formation. At least three non-cemented eolian units, which belong to the Present Interglacial (MIS 1), have been identified and appear interbedded with blackish soils with high organic matter content. The ^{14}C dating of gastropod shells from the top of the lower eolian unit yielded an age of 4.370±40 ^{14}C a BP.

Modern Optically Stimulated Luminiscence (OSL) techniques where used to establish the chronological framework of the Upper Pleistocene deposits from north-eastern Mallorca (Fornós *et al*., 2009). OSL datings (Figure 5) were made through the scarce quartz grains present in the eolianites that are thought to be deposited during dust rains related to aerosol components from the desert areas in North Africa (Fiol *et al*., 2005).

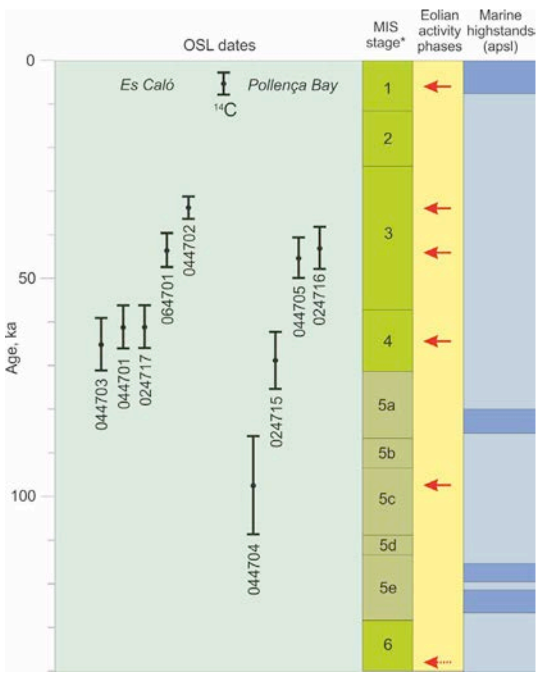

Figure 5. Main eolian activity phases since the Last Interglacial (modified from Fornós *et al*., 2009; [*] Source: Martrat *et al*. 2004)

OSL ages from eolian deposits separated by alluvial and fluvial deposits at the Bay of Pollença and in Es Caló study sites give ages of 97±12 kyr, suggesting eolian deposition during MIS 5c or 5b. The 69±7 to 61±6 kyr ages advocate for a renewed eolian deposition during the MIS 4 and parts of the MIS 3 (45±5 kyr to 43±5kyr). An additional period of eolian deposition, belonging to the end of MIS 3 appears at the uppermost eolian unit that overlaps a fluvial entity yielding age values of 33±0.5 kyr. All these datings are similar to those reported by Rose *et al*. (1999) in Caloscamps location and also in the north-eastern Mallorca.

5. Dune systems

5.1. Cliff-top Middle Pleistocene eolianites

At most localities on Mallorca, the Middle Pleistocene eolianites and associated paleosols form impressive cliff-top deposits with individual layers that have extensive lateral continuity (Nielsen *et al*., 2004). Upper Pleistocene eolianites located in the depressed areas also show similar characteristics and the most prominent eolianites appear in the Pliocene to Middle Pleistocene sedimentary sequences, which cover most of the depressed areas of Mallorca and exhibit the typical large-scale cross bedding. Eolian deposits are composed of sets of trough-shaped and sometimes even tabular, 1 to 2 m thickness, although occasionally they can reach more than five meters with foresets dipping up to 30º. In some places the presence of rizhocretions is abundant and they can obliterate all of the sedimentary structures. Most deposits have a sheet-like geometry, suggesting an intense deflation after their deposition. Nevertheless, in some cases, the eolian dune facies shows a low-relief lens-shaped geometry suggesting the preservation of the original morphology. Occurring within the aforementioned eolian deposits, another type of deposit (i.e., corresponding to eolian sand-sheets) can be recognized. They form sheet-like layers with thickness ranging from 1 to 3 m.

Usually, they appear structureless although rare horizontal or very low-angle dipping strata can be observed. The lack of physical sedimentary structures in this kind of deposit can be explained by the common presence of rhizocretions. A classical location corresponding to the Middle Pleistocene is the Els Bancals succession (Figure 6) in the southern part of Mallorca (Nielsen *et al*., 2004).

5.2 Cliff-front Upper Pleistocene eolianites

Topographically controlled eolian accumulations (cliff-front) comprise echo dunes, climbing dunes and sand ramps (Livingston & Warren, 1996; Lancaster & Tchakerian, 1996). Along the eastern coast of Mallorca, spectacular eolian accumulations appear in front of a cliffy coast that ranges 20 to 30 m in height (Figure 7). When this continuing cliff is disrupted by an embayment, the eolian accumulations are especially well developed. Sea cliffs shaped in Upper Miocene calcarenites and limestones show several wave-cut platforms at 3 and 10 m a.m.s.l related to sea-level highstands (Clemmensen *et al*., 2001). Those limestone cliffs experienced a noticeable retreat since the Middle Pleistocene (Fornós *et al*., 2005) and probably reached their present position and morphology a short time before the deposition of the eolian accumulation during the Last Interglacial.

Figure 6. The Pleistocene succession at Els Bancals section formed by eolian units (A1, A3, A5) alternating with red colluvial deposits. Arrow indicates a wave-cut platform (modified from Nielsen *et al*., 2005).

Figure 7. Field appearance of the Late Pleistocene cliff-front accumulations near Pedreres des Bauç. Height of cliff in the distance approximately 35 m.

The cliff-front sediments can be divided in two sedimentary cycles; each is initiated by colluvial deposits and overlain by dune deposits. The dune deposits in the lowermost cycle are climbing, echo dune deposits, while those in the uppermost cycle are ascending dune deposits. The colluvial deposits that separate the two dune deposits contain eolian sand ramp deposits (Clemmensen *et al.*, 2001).

The echo dune deposits of the lowermost cycle shows a large-scale, critical to supercritical climbing dune cross-stratification (Clemmensen *et al.*, 1997) with well-developed seaward facing stoss-side deposits with surfaces dipping normally between 15 and 25º (rarely more than 30º) and cliffward facing lee-side deposits with its surfaces between 20 and 26º dip (rarely reaching dips larger than 32º). In cross section the dune brink line varies from sharp-crested to rounded, the latter form being associated with reactivation surfaces. Very often the strikes of the eolian dune deposits follow the coastal morphology alignment.

Marine carbonate sand was deposited as dunes in front of steep cliffs separated from the sea by a coastal plain larger than 2 km in width assuming a sea level 50 m lower than today (Bradley, 1999). Dating suggest that deposition took place around 40 kyr (Clemmensen *et al.*, 1997; 2001). The exposed dune heights in eastern Mallorca can reach more than 30 m, although they should be higher due to the fact that dune bodies continue beneath the present sea level. Sand transport inferred from sedimentary structures shows a trend perpendicular to the coast morphology, similar to the current eolian sediment transport in the island dune systems (Servera & Rodríguez-Perea, 1999).

The eolian deposits that appear in the basal part of the second sedimentary cycle formed in a classical sand-ramp configuration (Lancaster & Tchakerian, 1996). They appear as 3 m thick packages of eolian sand, dipping away from the cliff between 20 and 30º; the eolian deposits are closely associated with colluvial (talus) deposits. The sand ramp takes on the present height of the cliff in many locations.

The colluvial deposits form discrete layers that never reach more than 2 m thick and that appear interbedded with the eolian sediments. They are composed of breccias with scattered, very poorly classified angular limestone clasts, floating in a red (silty) matrix. The sharp and mostly erosional contact with the underlying echo dune deposits contrasts with the gradual transition to the overlying eolian deposits. The colluvial deposits represent debris flow avalanches going down over the slope of the eolian sand accumulation in front of the cliff.

The ascending dune deposits of the uppermost cycle show large-scale, landward dipping cross-bedding, with typical set heights between 1 and 2 m. Part of the dune cross-bedding has been disrupted by root casts, stem imprints and animal tracks. The dunes formed on top of the ramp and especially in areas where the ramp was lower than the cliff. Dune formation was related to a new input of marine carbonate sand from the coastal area.

The alternation of colluvial and eolian deposits records the transition from relatively humid (colluvial) into arid (dunes) climatic intervals. This scenario can tentatively be related with two Dansgaard-Oeschger cycles (interstadial and stadials) during MIS 3 (Clemmensen *et al*., 2001) that coincide in the Mediterranean area with a special dry climate period (Rossignol-Strick & Planchais, 1989).

5.3 Eolian - fluvial Upper Pleistocene successions at slopes or low cliffs toe

The second group of eolian deposits comprises systems deposited over a gentle slope or low cliffs. The coastal outcrops of Upper Pleistocene deposits in northeastern Mallorca (Alcúdia and Pollença bays) record such a system with a complex interaction between eolian, colluvial, and alluvial fan deposition (Fornós *et al*., 2009). This interaction results in a variable stratigraphical architecture of the alluvial fan - dunefield system that overlies the Eemian (MIS 5e) beach deposits (Rose *et al*., 1999).

The facies architecture of the systems varies considerably and reflects the pre-existing morphology as well as the complex interaction between eolian, colluvial and alluvial fan deposition. The existing relief controls both the eolian and the slope-alluvial processes that contribute to build up the deposits.

At Alcúdia Bay, the Upper Pleistocene facies are located at the piedmont of the Serres de Llevant (Figure 8). Alluvial fan deposits appear here and exhibit a large variability of facies and, in some parts of the alluvial fan systems, the eolian facies are

Figure 8. Eolian sand bodies, water-reworked eolian deposits and water-laid alluvial fan deposits cause the complex stratigraphy of the system at Es Caló (Alcúdia Bay), where the Upper Pleistocene facies are located at the piedmont of the Serres de Llevant.

dominant (Gelabert *et al*., 2003). The sediment bodies and facies have a great lateral variation along the coast with a local architecture that reflects the relative position with respect to the axis of the alluvial fan and to the influx of eolian sand from the coast. The proportion between eolian sand bodies, water-reworked eolian deposits and water-laid alluvial fan deposits cause the complex stratigraphy of the system. In the coastal sequence, three main eolian units can be distinguished (Figure 8): the eolian deposits are interbedded with alluvial deposits (sheet-flood, fluvial channel and especially, water-reworked eolian deposits), as well as with some paleosols. The two lowermost eolianites correspond to migrating crescent dunes that were not obstructed by inland cliffs. They are large-scale with cross-stratification and with wind ripple lamination and sand-flow stratifications. Their inland migration was apparently only controlled, apart from the dominant westerly wind, by the amount of water flow from the alluvial fan. The uppermost eolianites are located at the top of the cliff exposure in near contact with alluvial fan deposits.

At Pollença Bay, the basement morphology consists of crenulated cliffs shaped in Jurassic rocks that control the overall architecture of the Upper Pleistocene deposits formed by cliff-front dune, sand ramp, rock fall, alluvial fan and colluvial deposits as well as by some paleosols (Figure 9). The thickest eolian deposits are located in front of the steep cliffs whereas alluvial fan deposits are best developed in the intervening low-relief areas. The eolian deposits form three overlapping units. The lowermost eolian deposit is a cliff-front dune unit that overlies coastal cliff-toe breccias and cobble beach deposits (MIS 5e?). The eolian deposits are characterized by the typical cross-stratification composed of well-developed topsets and foresets indicating an asymmetric dune moving inland. The second eolian deposit corresponds to an ascending dune or sand ramp that develops over a thick paleosol, which can be followed laterally along wide sectors of the cliff outcrops. Finally, the third eolian unit is new ascending dune deposit that shows wind-ripple lamination and sand flow stratification; this unit, which onlaps alluvial fan sediments, is overlain by younger colluvial deposits (Fornós *et al*., 2009).

Figure 9. At Pollença Bay, the basement morphology of crenulated cliffs shaped in Jurassic rocks control the overall architecture of the Upper Pleistocene deposits formed by cliff-front dune, sand ramp, rock fall, alluvial fan and colluvial deposits as well as by some paleosols. Height of the cliff (left side) *ca.* 18 m.

The interbedded non-eolian deposits vary locally, in some parts consisting exclusively of alluvial fan facies (sheet-flood, channel deposits) whereas in other parts they include water-reworked eolian deposits. This latter facies evidences the contemporary eolian sand transport and alluvial fan activity.

There are differences in the stratigraphic setting of the eolian deposits at Alcúdia (es Caló) and Pollença Bays, but these can readily be explained in terms of differences in local topography and according to the distance from watersheds to the sea. Cliff-front dunes and related ascending dunes, as well as sand ramp deposits appear seaward of steep inland cliffs (Pollença), while ordinary migrating dune deposits relate with distal alluvial fan areas (Alcúdia). Both sequences record four phases of eolian activity between MIS 5c and MIS 3 (Fornós *et al*., 2009) as described above.

6. Implications for landscape and sea level evolution

6.1. Paleoclimatic and paleoenvironmental implications during the Middle Pleistocene

Regional studies of Mediterranean soils formed during the Pleistocene interglacial periods highlights that they are usually reddish and have high magnetic susceptibility and negative $\delta^{18}O$ values (El-Asmar, 1994; Rose *et al*., 1999). These attributes suggest that the climate was warm and moist during soil formation. Studies by Gunster & Skowronek (2001) indicate that Pleistocene soil formation occurred under warm and moist (interglacial or interstadial) conditions with dense vegetation cover and a stabilized landscape. In contrast, the eolianites are thought to record arid glacial or stadial periods and therefore they were formed during sea-level lowstands (cf. Butzer, 1975).

The Els Bancals sequence constitutes the reference location for the Middle Pleistocene at Mallorca. According to Nielsen *et al*. (2004), the colluvial soils that appear interbedded with eolianites at Els Bancals record warm and moist conditions. The relatively thick and dark red colluvial soil complexes containing prominent magnetic susceptibility values likely record prolonged periods of warm and relative humid climate, and was thus probably formed during interglacial periods.

In this way, eolian deposits from Mallorca would differ from other common Pleistocene eolianites, which formed during sea-level highstands (Brooke, 2001). Thus the terrestrial part of the Middle Pleistocene succession at Els Bancals seems to record from the base to the top: interglacial climate and colluviation, glacial climate and episodic dunefield formation, a second period of interglacial climate, and finally glacial climate and episodic dunefield formation. In the glacial periods, interstadial and stadial conditions alternated with eolian activity during the stadials and colluvial soil formation during the interstadials.

6.2. Paleoclimatic and paleoenvironmental implications during the Late Pleistocene

The Late Pleistocene composite sequences of eolian, colluvial, and fluvial facies present in the coastal areas of north-eastern, south and south-eastern Mallorca, along with new stratigraphic and OSL chronologic data, indicate that deposition of eolian sediments took place during the colder, probably more arid, and windier periods, when the sea-level was lower than present. Probably a decrease in vegetation cover would allow sand transport inland from exposed shelf areas. This interpretation is supported by the presence of semi-arid vegetation in southern Mediterranean associated with a drastic reduction of temperatures and precipitation during cold climatic intervals (Bout-Roumazeilles *et al*., 2007). The eolian and fluvial deposition were linked to cold climatic intervals between 95 and 35 kyr. These were also the periods of lower sea level and maximum exposure of carbonate shelf and shoreline deposits. If winds were strong enough, during these stages this material would have been transported inland in the form of migrating dunes.

Four main periods of eolian activity with formation of dune deposits can be identified and related with different isotopic stages. The first one, ordered from base to top, occurred during MIS 5c or 5b at about 97 kyr. This was a period of intermediate sea level (-10 to -20 m in Mallorca; Tuccimei *et al*., 2006; 2012). During this time, annual mean sea surface temperatures were falling from around 20ºC at about 100 kyr to around 15ºC at about 90 kyr (Martrat *et al*., 2004). Mean annual land temperatures were 17.9-13.6 ºC in MIS 5c, but only 10.8-7.6 ºC in MIS 5b (Rose *et al*., 1999). Modern day mean annual temperature is 17.3ºC. A second period of eolian activity, MIS 4 at about 65 kyr, was a period of low sea level (Siddall *et al*., 2003; Rabineau, *et al*., 2006); annual mean sea surface temperatures were as low as 12ºC (Martrat *et al*., 2004), and mean annual land temperatures were likewise low, with estimated values between 8.2 and 4.9ºC (Rose *et al*., 1999). A third period of eolian activity and dune formation accounts in the middle part of MIS 3 at about 45 kyr. Sea level remained low (Siddall *et al*., 2003; Rabineau, *et al*., 2006); annual mean sea surface temperatures were around 15ºC (Martrat *et al*., 2004), while mean annual land temperatures were between 14.6 and 9.9 ºC (Rose *et al*., 1999). The final period of limited eolian activity corresponds to the end of MIS 3 at about 34 kyr. This was a period of low sea level (Siddall *et al*., 2003; Rabineau, *et al*., 2006); annual mean sea surface temperatures were around 12ºC (Martrat *et al*., 2004).

From the data obtained, it seems clear that episodes of eolian activity and dune formation can be linked to periods of low sea level, when extensive parts of the shore and platform carbonates would have been exposed to wind transport. Also, the vegetation cover would have been limited and rivers must have been an effective erosive agent inland (Rose *et al*., 1999) during these cold climatic intervals. Winds were probably stronger, and coastal dunes would have been able to move inland until they were trapped in front of inland cliffs or in the distal part of the coastal alluvial fans. Similar weather conditions as today probably were responsible for the inland transport of eolian material during cold climate intervals in MIS 5c/b, 4 and 3. Inland wind transport of marine carbonate sand currently takes place primarily during the winter. Strong westerly and northerly winds are common, with mean velocities higher than 8 m/s blowing more than 10% of the time (Servera, 1997; Jordi *et al*., 2006).

The dominant fluvial deposition that took place just after 65-70 kyr in MIS 4 eroded the underlying eolian sediments; preservation was controlled by early lithification and also made possible by a rising base level at about 65 kyr causing only limited fluvial incision. A second and more extensive phase of fluvial deposition took place just after

45 kyr in MIS 3, which resulted in alluvial fan formation at both sites (Pollença and Alcúdia Bays). Rose *et al*. (1999) also suggest that MIS 2 was a period of significant landscape change and extensive fluvial and eolian activity.

OSL ages of eolianites from Sardinia indicate that the northwestern coast of this island was covered by dunefields in MIS 4 (Pascucci et al., 2008). Similarly, in Mallorca, intense inland transport of eolian sand occurred during MIS 4. Great dunefields covered large parts of the coastal areas along the bays of the north-eastern part of the island. These results suggest enhanced storminess in large parts of the western Mediterranean during this cold period. This interpretation is supported by climate simulations indicating a decrease in winter storm days during the warm MIS 5e (ca. 125 kyr) and an apposite, but weaker change in storm activity during the beginning of the relatively cold MIS 5d (115 kyr; Kaspar *et al*., 2007). Data from the Alboran Sea also suggests an intensification of northwesterly winds in the western Mediterranean Sea during cold climatic intervals (Moreno *et al*., 2002).

Recent palaeoclimatic data inferred from vadose spelothems isotopic composition from Mallorca (Hodge *et al*., 2008) show environmental changes during the Last Interglacial period. In MIS 5e (130 to 120 ka) an evolution from pluvial to more arid conditions is seen. Additionally during MIS 5a (85 a 80 ka) there was marked climate variability with abrupt changes in temperature and precipitation in periods shorter than 200 years. Otherwise MIS 4 and MIS 3 relate to dry and cold episodes.

7. Other aspects

7.1 Rhizocretions

In the dune deposits, and especially beneath the colluvial and paleosol horizons, extensive root structures are developed in many sizes and styles (Calvet *et al*., 1975; Esteban & Klappa, 1983). Smaller plants colonizing dunes commonly develop root networks parallel with lamination and their structures are easily overlooked (Loope, 1986). Conspicuous root structures are common in most of the dune deposits, except in the echo dunes where there is little evidence of the presence of such structures indicating a scarce colonization by the vegetation.

The rhizocretions are a characteristic diagenetic structure of eolianites present in Mallorca. These carbonate concretions are formed by preferential cementation around the roots of the vegetation on the dunes. They are characterized by a vertical orientation (Figure 10) and locally they present branching forms with sections ranging from millimeters to several centimeters in diameter and in some cases of metric order in vertical dimension (Calvet *et al*., 1975; Ward, 1975). The presence of laminated concretions (crusts) and caliche related paleosols (Klappa, 1978) are also very common, highlighting the presence of a spherical microstructure formed by radial calcite prisms and produced by the calcification of *microrizae* associations called *Microcodium* (Esteban & Klappa, 1983). The massive presence of all these structures can obliterate the entire lamination of the dune system (the "*dikaka*" of Glennie & Evamy, 1968).

Figure 10. The rhizocretions are a characteristic diagenetic structure of eolianites present in Mallorca. Widt of rhizocretions *ca.* 2 cm.

7.2 Ichnology: Tracks and trackways of *Myotragus balearicus*

Tracks and trackways of the ruminant goat, *Myotragus balearicus* (Bate, 1909) are a common feature in the Pleistocene eolianites of coastal areas of Mallorca (Fornós *et al.*, 2002b). First described by Fornós and Pons-Moyà (1982) in a small quarry in the southeastern part of the island, they are ubiquitous in all Pleistocene littoral eolianites, and disappearing around 5000-4000 yr BP when the extermination of *Myotragus* occurred with the *Homo* arrival (Alcover, 2004).

The tracks can be observed in all the eolian units (Figure 11) being especially abundant in the cliff-front related deposits that correspond to the MIS 3 (Fornós *et al.*, 2002b), where tracks are abundant in the crestal zone deposits, common in the stoss-side deposits and rare in the lee-side deposits of the dunes. There are thousands of laminae in the lithified eolianites that have been tracked by this ruminant goat endemic to the Balearics. The extensive sections provided by the quarry exploration of the calcarenites for building purposes, parallel and perpendicular to the bedding, allow seeing the track in vertical as well as in horizontal sections. Plastic deformation and microtectonic rupture in the form of microfaults and microthrusts are involved in the sediment disturbance caused by the trace maker.

Almost all exposed bedding surfaces show horizontal sections, both epirelief and hyporelief, of tracks at various levels beneath the tracking surface. When observed

Figure 11. Ichnology in the Upper Pleistocene eolianites: (a) Insect trace fossils; (b) bifid foot impressions of *Myotragus* seen in distal transverse sections; (c) Perpendicular sections of tracks showing the distubed dune lamination; and (d) two trackways of *Myotragus* at the dune crest.

from a section concave-up, deformation structures are common corresponding to the downward fading deformation of the subjacent laminae within the substrate.

The tracks formed in the dune deposits and all of the preserved trackways indicate impression into moist sand. Special features of the tracks include the structure produced by the withdrawal of the foot, and an adjacent disturbance zone of plastic deformation. On dune crests, the disturbance zone surrounds the axis more or less symmetrically. However, in addition, a "pressure pad" of dislocated, slightly rotated sediment bound by curved microfaults, is commonly produced posterior to the axis by propulsive pressure of the foot. On steep windward and lee slopes, the pressure pad becomes oriented in a downslope position as a result of gravitational slip of the walking animal.

Combination of disturbance of the sediment in this way by *manus* followed by overprinting of similar disturbance by *pes* produces highly complicated track structure. This structure may be characteristic of artiodactylous mammals in soft sand, particularly eolian deposits.

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